RESEARCH COUNCIL OF ALBERTA

Hail Studies Report 71-1

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Part 1 — The Development and Testing of an Airborne Droppable Pyrotechnic Flare System for Seeding Alberta Hailstorms

by

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PETER W. SUMMERS
Research Council of Alberta, Edmonton, Canada

GRAEME K. MATHER
DENNIS S. TREDDENICK
National Aeronautical Establishment Ottawa, Canada

Research Council of Alberta
Edmonton Canada
February 1971

Additional copies $1.00 each

PREFACE

The Alberta Hail Studies Project is sponsored jointly by the Research Council of Alberta, the National Research Council and the Meteorological Service of Canada. Much of the data analysis is contracted to the Stormy Weather Group of McGill University, Montreal.

The project began collecting data on hailstorms in Alberta in 1956. Substantial progress has been made in developing models of hailstorm kinematics and the growth of hailstones within the storm. Whilst still far from complete, the understanding of hailstorms has now reached the point where worthwhile experiments can begin. The eventual aim of these experiments is to develop cloud seeding techniques capable of interfering with the natural growth of hailstones such that the amount and size of hail reaching the ground causes less crop and property damage. The economic potential of such a seeding system is self-evident, since damage to crops alone is estimated to averate $20 to $30 million annually in Alberta.

A seeding concept applicable to Alberta hailstorms was developed. The National Aeronautical Establishment in Ottawa was requested to provide an aircraft and the engineering required to convert it into a seeding platform. This report describes how the seeding system was developed, provides data on the flare performance and discusses the logistics involved in its use. A second report will contain detailed case studies of the seeded storms of 11 July and 9 July 1970.

Peter W. Summers,
Field Coordinator,
Alberta Hail Studies.

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ABSTRACT

Most severe persistent type Alberta hailstorms propagate at an average of 25° to the right of the mid-tropospheric winds by means of new cloud development continually occurring on the southern flank. A seeding concept, whereby these cumulus towers are seeded early in their development, is proposed. To accomplish this a droppable pyrotechnic system was developed.

Seven inch pyrotechnic flares were manufactured by Olin Corporation. Each flare contained a delay fuse of 60 sec after which the 24 gm silver iodide mixture burned for 30 sec. Total fall distance was approximately 10,000 ft. A unique feature of the flares was the incorporation of 10 cm radar chaff which was released as a marker at the end of the burn. The flares were tested using radar, visual and photographic tracking and their performance evaluated. A T-33 jet aircraft was equipped with a weather radar, a rack capable of carrying 52 flares and a firing control system.

The seeding system was used for five experiments in Project Hailstop conducted as part of the Alberta Hail Studies field program in July 1970. Evaluation of the experiments will emphasize physical rather than statistical parameters. On two occassions turbulence measurements were made in cumulus towers by a second T-33 aircraft. Calculation of the dissipation rates indicate that there is sufficient diffusion to produce silver iodide nuclei concentrations in excess of 100 per liter active at -10C throughout a substantial volume of the cumulus towers within a few minutes of seeding.

The operational logistics of this seeding system are quite straightforward. By means of radio communication between the project radar control room and the seeding aircraft it was always possible to unambiguously identify and seed the selected target storm. The radar chaff was useful as a check on the targetting accuracy of the seeding.

INTRODUCTION

Hail occurs in central Alberta on an average of 66 days every summer, with 13 of these classified, on the basis of areal extent, as major hail days (Summers and Paul 1967). Over the last 33 years the Alberta Hail Insurance Board has recorded an average of 50 days per year with at least one hail damage claim filed from somewhere within the province. For each year of these insurance records during the period 1953 - 1969, the days were ranked in descending order of number of claims. The percentage of the year's total claims was calculated for the worst day, the second worst day and so on. All 17 years were averaged and the result is shown in Fig. 1. It can be seen that one half the year's total damage occurs on only four days and 80 per cent of the damage occurs on the 12 worst days. The remaining 38 days account for the other 20 per cent of the year's total damage.

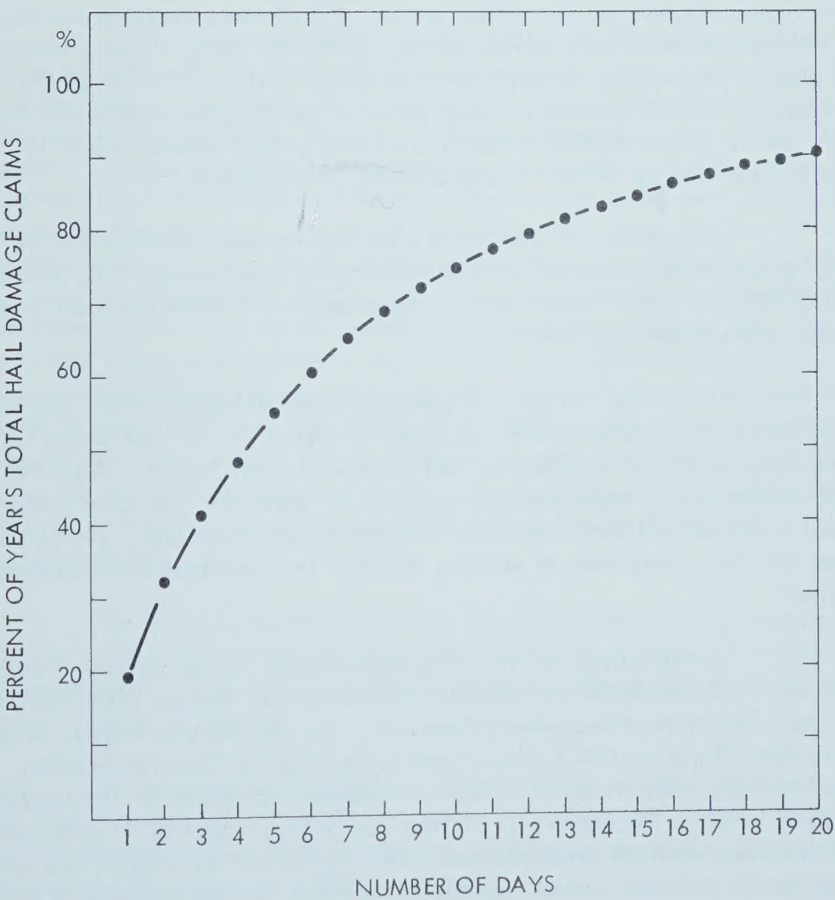

Fig. 1. Average number of days required to produce a given percentage of the year's total hail damage.

It is thus evident that an effective system of hail suppression in Alberta must be able to cope with the dozen or so worst days when the severe persistent type of storms produce the long damaging swaths.

A variety of techniques have been used during the last two decades to seed hailstorms with silver iodide. These techniques range from seeding of the whole airmass in which the storms are expected to develop to cloud-base seeding of the air entering single storm systems and more recently to the method of direct injection of the seeding material into a small volume of the cloud by means of projectiles. Schleusener (1968) has reviewed the results from many projects and concludes that the available evidence supports the hypothesis that major hailfalls can be reduced by heavy seeding rates ($>$2000 gm hr^{-1} AgI per storm).

The only projects to date which consistently show apparent reductions in hail damage over large areas are those conducted in the USSR since the mid 1960s. At last count the total area covered by seven separate projects amounts to over six million acres. All of these projects use the direct injection technique which not only produces heavy seeding rates, but also places the seeding material into a precisely defined volume of the storm. Sulakvelidze (1968) uses antiaircraft guns to fire frangible shells into the target zone. Other Russian projects are using ground-based rockets to carry the payload up to the desired altitude (Kartsivadze 1968).

In summary, whilst cloud base seeding may be effective in reducing hail from moderate intensity hailstorms (Henderson 1970, Schleusener et al.1970), the direct injection technique appears to offer the most promise for the severe travelling storms.

The use of antiaircraft guns and ground-based rockets is precluded in the hail belts of Alberta and the Great Plains of the United States because of the high density of commercial and private aircraft traffic. Also the very large number of gun emplacements required to cover the vast area susceptible to hail would almost certainly make the system uneconomical. An alternative system for direct injection of seeding material into hailstorms is therefore required.

Development on two different airborne rocket systems is currently underway at Colorado State University (Sinclair and Marion 1968) and the National Center for Atmospheric Research. For the Alberta storms, droppable pyrotechnic flares similar to those used in the Florida Cumulus Seeding experiment (Simpson et al.1970) were considered adequate for the seeding concept. Thus in December, 1969, the Research Council of Alberta asked the National Aeronautical Establishment (NAE) to furnish an aircraft and an experimental delivery system capable of meeting the requirements of the seeding experiments planned for the 1970 hail season in Alberta.

THE SEEDING CONCEPT

The question of when, where and with how many nuclei to seed a hailstorm to produce the optimum suppression effect is still far from being resolved. Several hail suppression concepts have been proposed but only two are currently accepted as being likely to succeed using present day seeding technology (MacCready & Vickers 1966, MacCready 1970). One approach is to seed with enough freezing nuclei to convert much or all of the growth medium from supercooled liquid water to ice. This requires vast numbers of nuclei and a means of distributing them through a large cloud volume in a short time.

The other alternative is to increase the number of hail embryos competing for the same given water supply, thus producing more, but smaller hailstones. This is the basis of the experiments in Russia (Sulakvelidze 1968).

There is considerable discussion as to whether either of these aims can be achieved by seeding at cloud base in the strong updraft region of a severe storm. The main objection is that of insufficient turbulence to diffuse the seeding material through a sufficient volume of the air feeding the storm. On two occassions measurements were made in Alberta storms by the University of Nevada,Desert Research Institute B-26 aircraft carrying a Meteorology Research Inc. Universal Turbulence Indicator. Values of the dissipation rate (ϵ) found in the strong updraft from cloud base to 15,000 ft MSL, were less than 3 cm^2 sec^{-3}, characteristic of smooth air (Berry 1970). In this strong updraft the rising parcel moves from cloud base to the -20C level in less than 5 min and under the turbulence conditions cited above the seeding plume produced by a single aircraft would only have expanded to a diameter of about 100 to 200 m (Smith et al 1968). Thus only a very small fraction of the total updraft volume would be seeded by this method. With a typical air flux value of 20 km^3 min^{-1}, less than one per cent of the total volume of air entering the storm would be seeded by the time the air parcel ascended to 8 km.

The method used in the USSR is to place the seeding material into the region aloft between the -5C and -12C levels where there is already a strong radar echo. This so-called "hail center" is where the maximum hail growth is thought to occur.

An approach not yet given serious trial is to introduce the nuclei into the wall areas of the echo weak region - usually well marked areas of high radar reflectivity (Chisholm, 1970) - by careful engineering of the seeding (MacCready 1970).

Yet another approach is to seed the developing cumulus towers or groups of towers on the southern flank of the storm. Analysis of time-lapse

movies and radar records of many Alberta storms shows that most, if not all, of the persistent type of storms propagate at an average of 25° to the right of the mid-tropospheric winds by means of new development continually occurring on the southern flank. Distinct new surges of activity appear at regular intervals (between 5 and 15 mins) as one or a group of large cumulus towers rising rapidly and then merging with the parent storm. These clouds are akin to the "feeder clouds" observed in South Dakota (Dennis et al. 1970), however in Alberta they seldom start as distinct separate entities. They begin either immediately adjacent to the parent storm, or are sometimes observed bulging out from the side of the parent storm at heights of between 10 and 20,000 ft.

The first radar echo usually appears in these new towers at about 20,000 ft. Shortly afterwards the towers lose their visual identity as they merge with the parent storm. However the radar echo rapidly grows in size and can be followed as a distinct entity as it moves in the direction of the midlevel tropospheric winds through the storm complex (Chisholm 1966). Thus, whilst the storm is persistent in the sense that it moves as an indentifiable system and lays an almost continuous swath of hail on the ground, large variations of intensity can occur. The hailfall pattern on the ground shows a series of pockets of larger hail, or greater ice mass per unit area, which can be related to the passage overhead of the higher intensity radar cores.

Since the new surges of cloud towers are the regions which will be producing the hail 15 to 30 min later, a reasonable experiment would be to seed this region heavily in an attempt to freeze as much as possible of the new supply of supercooled water entering the storm system. Initially, updrafts in these towers are less than in the updraft core of the parent storm, and strong turbulence can be expected. These two factors would therefore produce more rapid diffusion of the seeding material and allow more time for ice crystal growth than in the updraft core.

THE EXPERIMENTAL CONCEPT

The experiments are being conducted under the designation Project Hailstop as part of the Alberta Hail Studies program. This program is a cooperative investigation into all aspects of hailstorms operated jointly by the Research Council of Alberta, the National Research Council of Canada, the Canadian Meteorological Service and the Stormy Weather Group of McGill University, Montreal.

Initially the experiments are emphasizing physical rather than

statistical evaluation. No fixed target area is defined, but all seeding takes place within the experimental area shown in Fig. 2. Suitable storms are selected and one or more successive new cumulus towers are heavily seeded. The storm system is then closely monitored during the ensuing two hours. All observed events can be then related to the precisely known place and time of the seeding event. Using the observational facilities built up by the Alberta Hail Studies Project over the past fifteen years (Renick 1970), many physical parameters are monitored. These include the updraft area under cloud base, radar reflectivity and radar depolarization in three dimensions, precipitation efficiency and rain-hail ratios, hail fallout patterns and hailswath characteristics, visual appearance of cloud recorded photographically from the ground and from aircraft, hail damage, freezing nuclei spectra and silver content of precipitation. Time series of these parameters are studied to see if changes are observed at a time after seeding consistent with the current theory of Alberta hailstorms. The spatial distribution of most of these parameters is also analysed to look for changes downwind of the seeding event. At this stage in the experiments, emphasis is being placed on detecting reproducible changes in some or all of the above physical parameters which may be attributable to the effects of seeding. If necessary, randomized statistical experiments can be designed around these parameters at a later date.

DESIGN CRITERIA FOR THE PYROTECHNICS

A study of 157 days with major hailswaths in Alberta over the last 13 years, shows that on these days the average height of the -5C level in the environment is 13,500 ft MSL. Inside the cumulus towers the -5C level would be at about 15,000 to 16,000 ft MSL. The mean depth of the target zone was therefore defined as 15,000 to 18,000 ft MSL.

Based on observations made by the T-33 aircraft that had been working in Alberta in previous years it was felt that most of the newly developing cloud towers could be detected visually from the seeding aircraft as the tops pass through about 15,000 ft. By the time the aircraft could reach the target the towers would have grown to a height of approximately 20,000 ft. The optimum aircraft seeding altitude should thus be between 20,000 and 25,000 ft to avoid having to penetrate the turbulent and rapidly rising cloud top on the seeding pass, and also to keep the flare fall distance as short as possible to minimize targetting errors. Allowing for mean updrafts of 5 to 15 m sec^{-1} inside the cumulus towers required that the flares have a free fall of between 10,000 and 12,000 ft in still air when dropped from a height of 20,000 to 25,000 ft. This determines the delay burn time required in the flares.

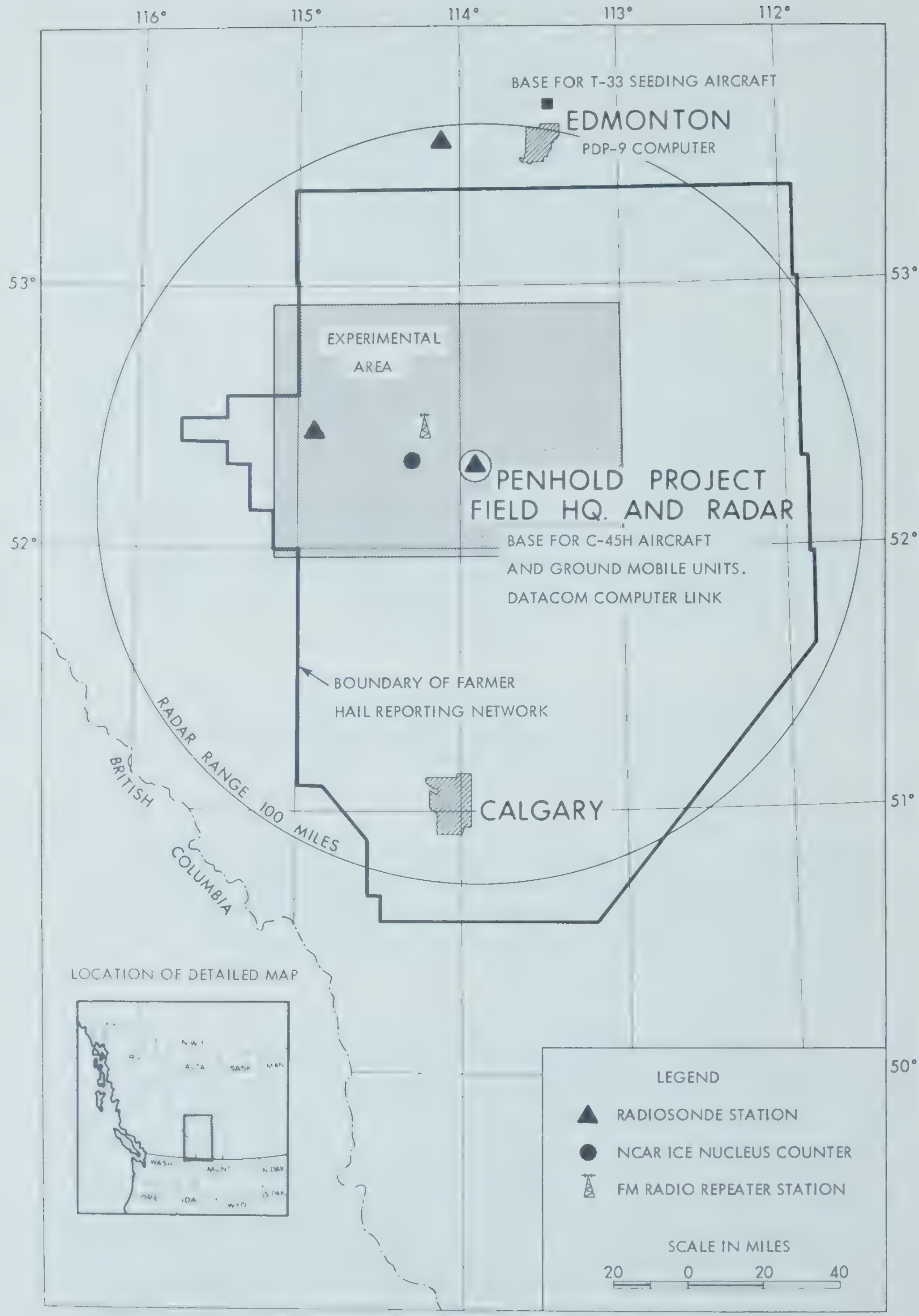

Fig. 2. Map showing the Alberta Hail Studies project area and deployment of facilities for Project Hailstop 1970.

The desired freezing nuclei content required in a substantial volume of the cumulus towers several minutes after seeding is at least $10^2 l^{-1}$ active at -10C. Using figures for the rate of diffusion in cumulus congestus clouds given by Smith et al (1968), the above concentration could be achieved by dropping the flares at 1000 ft horizontal intervals, if each flare generates at least 5×10^{13} nuclei active at -10C.

In February 1970, Olin Corporation were asked to manufacture twenty test flares with the following characteristics:

first fire and delay burn 50 sec
silver iodide mix burn 30 sec
total nuclei output active at -10C $>5 \times 10^{13}$.

Ten of the test flares were to contain, in addition to the silver iodide mix, a small bundle of 10 cm radar chaff. This chaff was to be released at the end of the silver iodide burn by a small expulsion charge so that radar detection could be used for confirming targetting accuracy. Twenty such flares were delivered by Olin in May, 1970. A schematic of the flare cartridge is shown in Fig. 3.

THE SEEDING AIRCRAFT

The National Aeronautical Establishment of the National Research Council of Canada participated with the Research Council of Alberta in the 1970 hail research program by modifying and instrumenting a T-33 jet aircraft (Fig. 4) to fulfill the requirements for a seeding aircraft. The T-33 is a rugged aircraft easily capable of achieving the altitudes required for on-top seeding and it has sufficient speed and maneuverability to meet the rapid deployment needs of the experimental design.

Seeding pod

A 52 round pyrotechnic rack capable of accepting the 7 inch flares was purchased from Olin Corporation. The rack was installed in an extensively modified T-33 luggage pod (Fig. 5). When the pod is on the aircraft, the two 26 round magazines detach from the rack through the bottom of the pod by the removal of one bolt from each. The total system can be reloaded in less than two minutes.

Firing control panel

Firing of the flares is controlled from a panel located in the

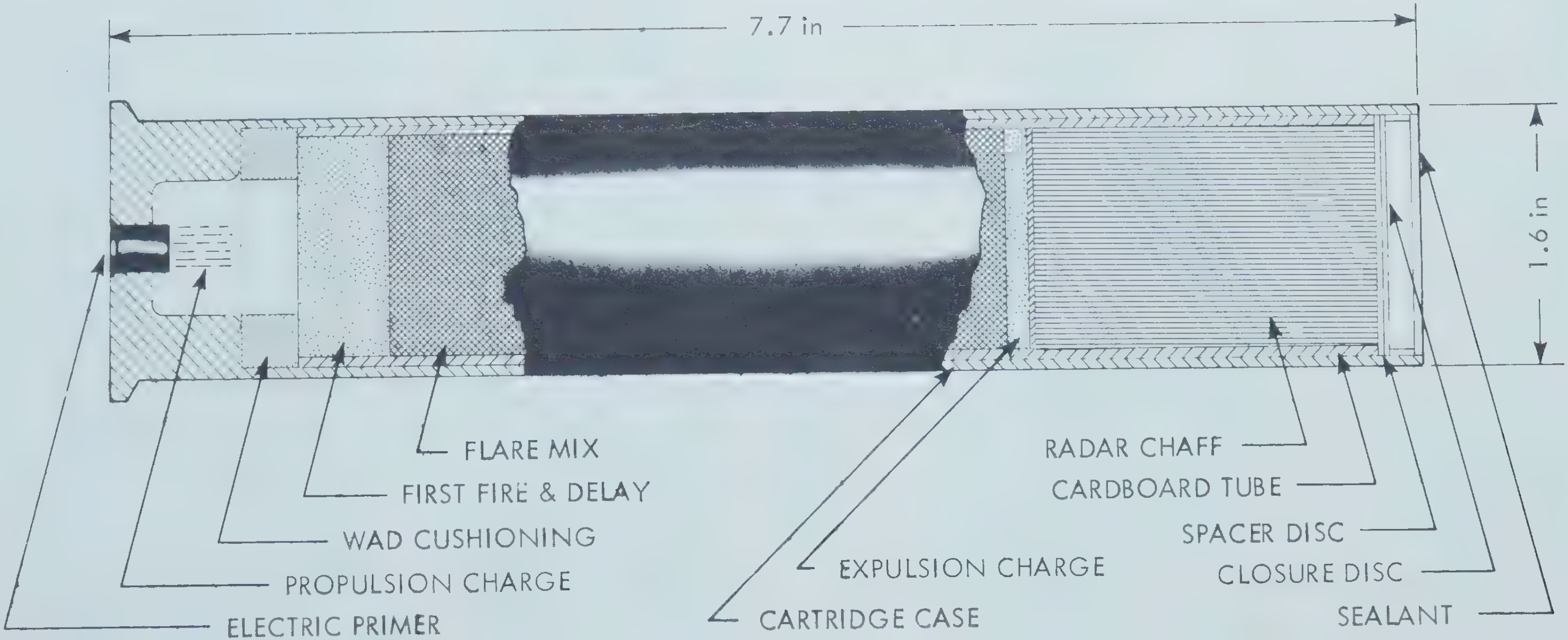

Fig. 3. Cut-away diagram of the pyrotechnic seeding flare containing radar chaff.

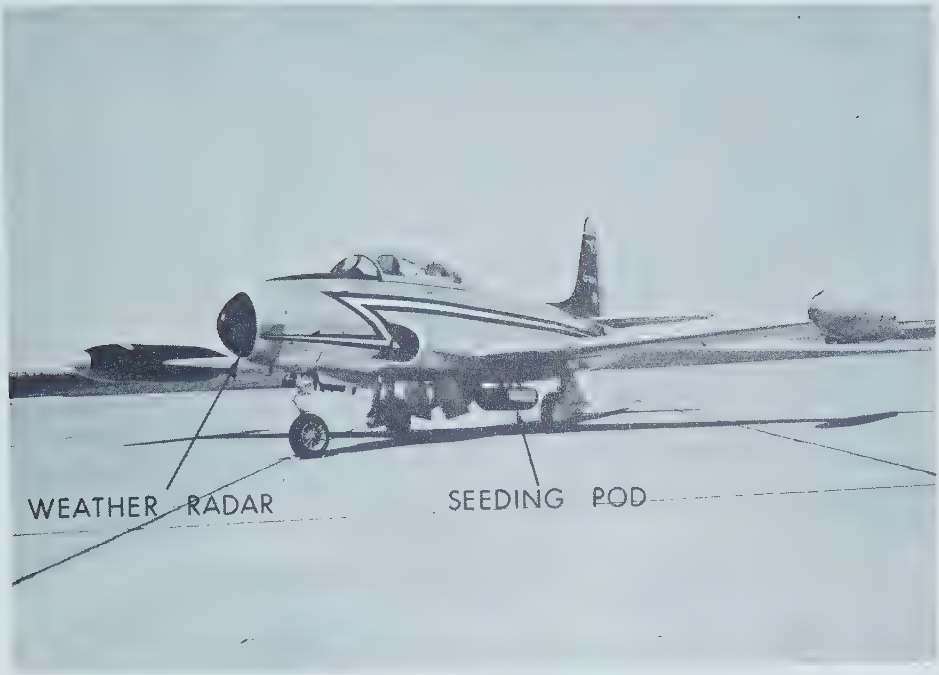

Fig. 4. The National Aeronautical Establishment T-33 seeding aircraft.

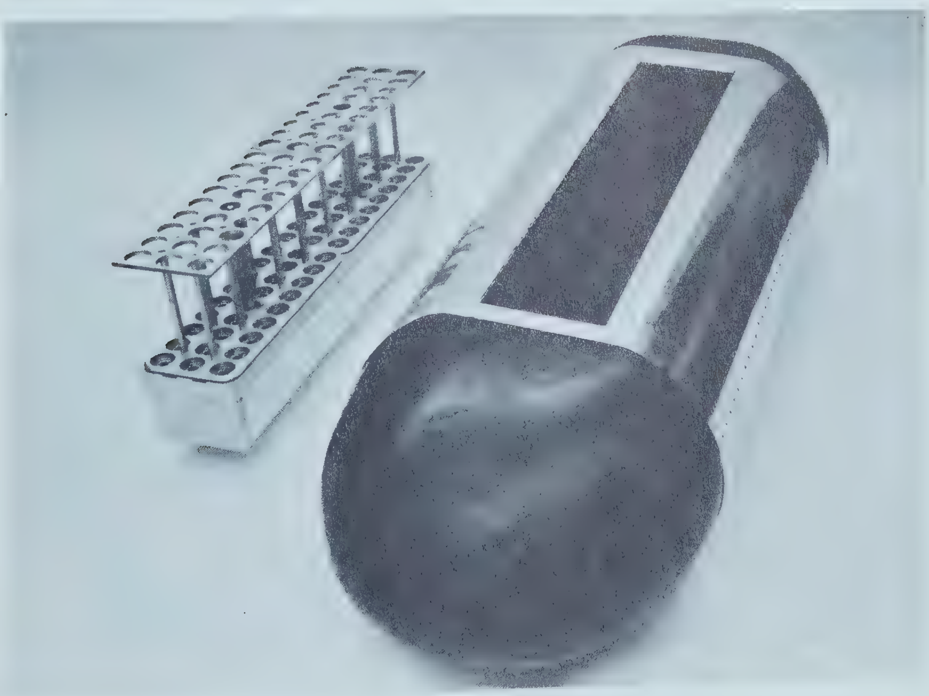

Fig. 5. The seeding pod and flare rack.

rear seat position of the T-33 as shown in Fig. 6. The flare rack is electrically split into two banks; one for twenty chaff flares and the other for 32 no-chaff flares. Firing control is directed to either bank by a toggle switch so that any choice of a chaff/no-chaff flare pattern can be freely selected on a seeding run. Each bank has a separate counter and reset switch. Other controls on the panel are a main power switch and an arm-disarm switch. Lights indicate power on, flare rack empty (one light per bank), pod fire warning and that the magazines are secure in the rack. The flares are fired singly from either the front or rear seat positions by a push button mounted on the aircraft control stick.

Instrumentation

A 14 channel galvanometer film recorder was installed in the nose section of the aircraft. Using a film speed of 6 mm sec^{-1}, one hour and twenty minutes of continuous recording is available. Parameters recorded are:

(i)	altitude	(v)	time code
(ii)	airspeed	(vi)	flare firing
(iii)	total temperature	(vii)	manual event marker
(iv)	normal acceleration		

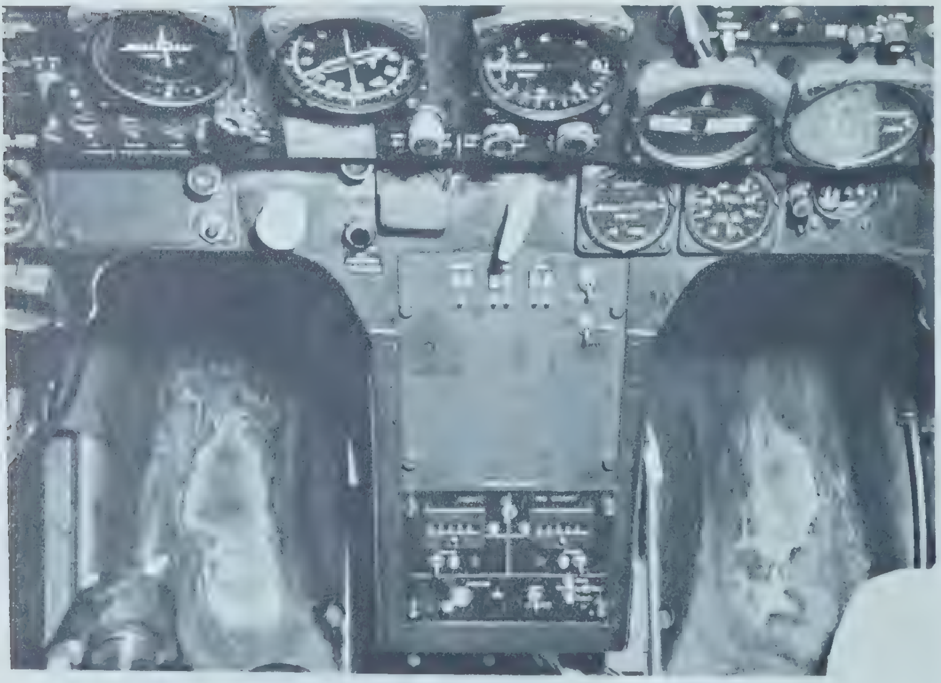

Fig. 6. The flare firing control panel and digital clock.

A voice recorder was installed in the back seat and wired into the aircraft intercom system, recording all air to ground transmissions and pilot comments.

A digital clock with a numerical read-out in hours, minutes and seconds was fitted above the firing control panel. Switches below the numerics display allow the clock to be synchronized exactly to the project master time clock at the beginning of each mission. A time reference in binary code is placed on the film recorder every two minutes.

Weather radar

A Ku band weather radar, with a maximum range of 90 nautical miles, was installed in the nose of the T-33. This entailed considerable modification to the nose structure of the T-33, and construction and installation of a custom-built radome. The radar scope and controls were mounted on the instrument panel in the rear seat position.

Photographs

A hand-held 35 mm camera was used from the back seat to take photographs of the cloud towers before and after seeding to record any possible visible changes in the appearance of the clouds. The time of each picture was coded as a manual event on the film recorder.

The aircraft was manned by a crew of two who shared the duties of flying the seeding runs, camera and instrumentation operation and communicating with project control and the air traffic control center.

FLARE PERFORMANCE EVALUATION

Prototype flares

An initial batch of 20 prototype flares were delivered to the National Aeronautical Establishment for testing. On 20 May, 1970, ten flares were dropped at night over a restricted area on Lake Ontario. The drops were made from the seeding aircraft flying at an altitude of 25,000 ft, and observed from a Beech-18 circling below at 10,000 ft. All five no-chaff flares were successfully ejected from the pod. Four of the five ignited and were visually observed to burn for about 80 sec. Of the five chaff flares, four were ejected with only two igniting and burning for 80 sec. The fifth flare ignited but hung up in the rack where it burned itself out. The next day three more flares, two with chaff, were dropped. An air

traffic control radar was able to observe the successful deployment of the chaff. The expulsion of the flares from the rack was monitored from a second T-33 flying in formation with the seeding aircraft. The flares were observed to tilt forward when emerging from the rack, presenting the first-burn area of the ignited flare to the high dynamic pressure of the airstream. It was felt that this was the instant where a weakly ignited flare was being extinguished.

To determine the trajectories of the flares, the assistance of the tracking radars at Wallops Island was obtained. On 27 May, the aircraft was flown to Wallops Island where six flares were dropped from 26,000 ft and tracked by the radars. The results indicated that the flares dropped 6000 ft in the first 30 sec, 4000 ft in the next 30 sec and 2000 ft in the final 18 - 20 sec for a total fall distance of 12,000 ft in 80 sec. An analysis of the trajectories, corrected for wind drift, showed that the flares moved forward about 1500 ft from the release point before falling vertically.

Since the prototype flares met the design criteria a production run of 500 flares, with 70 containing radar chaff, was ordered for use in Phase I of Project Hailstop in July 1970. The production flares were to have a stronger propulsion charge to ensure positive ejection from the rack and an improved first fire mixture for more reliable flare ignition.

Production run flares

Ten of the production run flares were delivered to Ottawa just prior to the commencement of Project Hailstop 1970. In a night test flown on 2 July, an attempt was made to follow the burning flares down after firing, by flying a tight spiral around the flare trajectory. This proved to be a very successful method of observing flare performance. It was possible to follow the flares sufficiently closely to observe the change from delay to silver iodide burn and measure the total burn time and altitude of burn out. Table 1 summarizes the results of these tests on the production flares. All flares were dropped from 22,000 ft and times are from the instant of firing the first flare in each batch. Thus 8 out of 9 production run flares successfully ignited compared to only 6 out of 10 of the prototype flares. The change to a better first fire mixture appeared to increase the ignition reliability and also increase the total burn time. Table 1 indicates that the average burn time of the silver iodide mixture was 31 sec.

To obtain more information on the variation of fall speed with height and the relation between total flare fall distance and release height, a night test was conducted near Red Deer, Alberta in early August. A clear night was selected with light upper winds. The Alberta Hail Studies time-lapse photography system (Renick and Douglas 1970) was used to record the flare drops using only one camera. To simplify aircraft navigation and the photogrammetry, a radial from the Edmonton VORTAC was chosen as the flare drop line such that it was perpendicular to the camera axis at a range

Table 1. Summary of first test of production flares 2 July 1970

No. of flares fired	No. of flares ignited	Transition to AgI burn		Flare burn-out	
		Altitude (ft)	Time (sec)	Altitude (ft)	Time (sec)
1 Chaff	1		60		90
1 No-chaff	1		60	12,000	93
2 Chaff	2	15,000	57	11,500-12,000	85
5 No-chaff	4	15,000	55	11,500-12,000	90

of 10 mi. A trial run was made with two flares dropped to check on visual detectibility and the camera azimuth. Four runs were then made at altitudes of 18, 20, 22 and 24,000 ft with each run approximately 13,000 ft long. Two flares containing chaff were dropped close together at each end of the run for radar detection and ranging. Four no-chaff flares were equally spaced between the chaff markers. Of the total of 34 flares dropped, only two failed to ignite giving an ignition efficiency of 94%.

A pilot balloon was released at dusk shortly before the test. Except for a narrow zone of 15 kt winds between 11,000 and 12,000 ft, all winds were less than 10 kt. Thus during the flare fall, the total horizontal drift was less than 1000 ft. Errors introduced by change in range due to this drift were therefore less than 2%. The location of the chaff could be determined by radar to approximately 0.5 mi, thus giving a drop range accuracy of ±5%.

The time-lapse mechanism on the camera was adjusted to give a 0.5 sec exposure every 1.85 sec. The elevation angle for each flare on each frame was determined to the nearest 0.1° from a computer drawn projection grid, incorporating corrections for camera tilt. Height vs time graphs for each flare were then computed. Each group of chaff and no-chaff flares were averaged for each release altitude. Since Kodachrome II film was used, the flares could not be detected until they had fallen for 20 - 25 sec through one to two thousand feet and were well ignited. The times obtained from the photography are consistent with those obtained by the earlier radar and visual tracking. The exact height of the aircraft could have been recorded on the film by switching on the aircraft landing lights as done by Simpson et al (1970). However to do this on the T-33 requires lowering the landing gear and the flares would then have been dropped from the aircraft flying at considerably less than the normal operating speed. This in turn may have affected the performance of the flares during and shortly after release, and would not have simulated conditions on actual cloud seeding missions.

Because of the errors due to poor horizon markers at night and the ranging errors mentioned earlier it is estimated that the overall accuracy of measurements from the photographic tracking of the flares is $\pm 15\%$. Since the errors are more likely to be systematic rather than random, a comparison of results from the different release heights is still valid. Some of the characteristics of the flare performance obtained from the film record are summarized in Table 2 which indicates that the terminal velocity near the end of the fall is only about one third of that near the beginning. This is illustrated clearly in Fig. 7 which shows a series of 5 sec multiple exposures taken at 5 sec intervals with a 35-mm camera. The length of the bars near the end of the trajectory are much shorter than those at the beginning. The estimated track of the aircraft is superimposed on this photograph.

The depth of the seeded plume produced by each flare can be calculated, assuming a silver iodide burn time of 30 sec, and the results are shown in Table 2.

Another night test was run in Ottawa in November 1970, closely tracking the flares visually by spiralling down with them. The releases were all made from 22,000 ft - the typical release altitude during the actual seeding experiments - and the height of burn-out was obtained more precisely than in July. The results are shown in Table 3.

The important characteristic of the flare from the point of view of accurate targetting is the total distance fallen from release to burn-out. The results of all the tests are therefore summarized in Table 4.

Comparing the results of the camera and visual tracking for the 22,000 ft release height suggests that the photogrammetry has an error of approximately 1000 ft, or 10 per cent, in the height calculations. Until further tests are run using the stereo cloud photogrammetry system, this correction will be applied to the data in Table 4 which gives the best estimate of the relationship between flare fall distance to burn-out and release altitude. For each flare, the departure of the burn-out altitude from the mean value of its batch was calculated. The departures ranged from +950 ft to -600 ft with an overall standard deviation for the 30 flares of 346 ft. Thus 95 per cent of the flares will burn-out within $\pm$ 700 ft of the required altitude which is well within the desired experimental limits.

The chaff flares weigh 226 gm and the no-chaff flares weigh 197 gm. This difference in weight appears to have negligible effect on flares dropped from 18,000 ft. At higher release altitudes the slightly greater weight and the different mass distribution of the chaff flares appear to have a greater effect. However with drop altitudes of 20,000 to 24,000 ft the difference of up to 500 ft in fall distance is still small when using the chaff flares as altitude markers.

Fig. 7. Series of 5 sec multiple exposures at 5 sec intervals of nighttime release of eight flares.

Table 2. Summary of flare characteristics obtained by time-lapse photography 3 Aug 1970

Release altitude (ft)	Total fall distance to burn-out (ft)		Silver iodide only flares (no-chaff)		
			Mean terminal velocity (ft sec^{-1})		Depth of seeding plume produced during final 30 secs (ft)
	Chaff	No-chaff	First 10 secs photo tracking*	Final 10 secs	
18,000	8,000	7,975	198	71	2700
20,000	8,800	8,650	202	78	2600
22,000	9,650	9,400	193	71	2600
24,000	10,275	9,725	227	83	2900

*Approximately 25 - 35 sec after release.

Table 3. Results of visual tracking of flare drop from 22,000 ft 24 Nov 1970

Run	Flares		Transition to AgI burn		Burn out	
			Time (sec)	Altitude (ft)	Time (sec)	Altitude (ft)
1	1	No-chaff			89	12,500
2	1	Chaff			81	10,500
3	3*	No-chaff	60		86	11,300
4	3	Chaff		14,000	81	11,500

* 1 misfire.

Flare reliability

Table 5 summarizes the number of flares ignited compared to the number released on each of the tests with the production run flares. Of the total number of 51 flares released in the tests 47 ignited, thus giving an ignition efficiency of 92%. This is certainly adequate when dropping flares at close intervals on a seeding run.

Table 4. Summary of fall distances obtained by various tests

Method of tracking	Release height (ft)	Total fall to burn-out		Difference between chaff and no-chaff (ft)
		Chaff flares (ft)	No-chaff flares (ft)	
Radar (Wallops Island, May)	26,000	12,000		
Visual (Ottawa, July)	22,000	10,000–10,500	10,000–10,500	
Visual (Ottawa, Nov)	22,000	10,750	10,200	550
Time-lapse photography (Penhold, Aug)	24,000	10,275	9,725	550
	22,000	9,650	9,400	250
	20,000	8,800	8,650	150
	18,000	8,000	7,975	25

Table 5. Summary of ignition reliability of the flares

Test location & date	Number of flares released	Number of flares ignited
Ottawa, July	9	8
Penhold, Aug	34	32
Ottawa, Nov	8	7
Total	51	47

The silver iodide mixture

To achieve the required number of nuclei during a 30 sec burn, Olin Corporation used their WM 105 mixture. The composition of this mixture is shown in Table 6. Each flare contained 50 gm of the formulation and when burnt produced 24 gm of silver iodide. Tests performed in the Colorado State University cold chamber (Steele 1968) give the number of effective nuclei per gm of AgI as shown in Table 7. The last column in this table shows the total number of nuclei produced by the flare.

Table 6. Composition of Olin WM 105 formulation

Material	Per cent by weight
Silver Iodate	53
Oxidizer (Strontium Nitrate, Potassium Iodate)	19
Fuel (Magnesium, Aluminum)	18
Binder	10

Table 7. Nucleation efficiency of the flares

Temperature (C)	Effective nuclei per gm of AgI	Effective nuclei produced by flare
− 5	8×10^{10}	1.9×10^{12}
−10	1×10^{13}	2.4×10^{14}
−15	7×10^{14}	1.7×10^{16}
−20	4×10^{15}	9.6×10^{16}

SEEDING LOGISTICS

On a "go day", as soon as an active storm was detected moving east from the foothills, the University of Wyoming C-45H Twin Beech aircraft, which participated in the experiments, was despatched to investigate and map the updrafts in the manner described by Auer and Marwitz (1968). If the storm moved into the experimental area (see Fig. 2) and appeared to be a persistent type of storm, it was declared a seeding case. The ground mobile units were then despatched from Penhold and the crew of the T-33 aircraft standing by at Namao were scrambled. Contact with the T-33 was established as soon as possible after take-off and the latest location of the storm relayed to the aircrew. After positively identifying the chosen storm, the aircraft flew in a holding pattern at 30,000 ft 10 - 15 mi south of the storm. An airspace reservation, containing the holding pattern and the anticipated seeding area was then requested from the Edmonton Air Traffic Control Centre which always responded immediately. The rapid allocation of airspace greatly facilitated the smooth operation of the project and is essential to the logistical success of this seeding technique. The emergence of seedable new developments on the storm's southern flank had to be recognized from the seeding aircraft, since initially the new cumulus towers produce no radar echo. The T-33, photographing the storm from its holding pattern, advised project ground control as new seedable cumulus towers appeared. If the ground mobile units were in position and the Wyoming C-45H aircraft was safely clear of the drop area, then the go-ahead to seed was given. The seed/no-seed decision by project control had to be made less than a minute after recognition of the new development by the T-33 or that seeding opportunity was lost.

The actual drop altitude was determined from the following parameters: the estimated height of the -5C level inside the cloud determined from the latest sounding, an estimate of the updrafts expected in the cumulus tower and the known fall distance of the flares to burn-out in still air. As it turned out, all seeding runs were made between 21,000 and 23,000 ft. Flares were dropped every 2 sec, or approximately every 1000 ft, over the longest dimension of the cumulus tower, usually in a west to east direction. When the seeding was close enough to the project weather radar, chaff flares were often used as position markers at the end of the seeding run.

After the seeding run, the T-33 returned to its holding pattern south of the storm and continued to photograph cloud development. A decision was then made on whether or not to seed the next developing cumulus tower. The logistics are illustrated schematically in Fig. 8.

Meanwhile the ground sampling units were directed from Project Control into the area where precipitation from the seeded cell was expected to fall. Fine adjustment of the sampling positions was sometimes

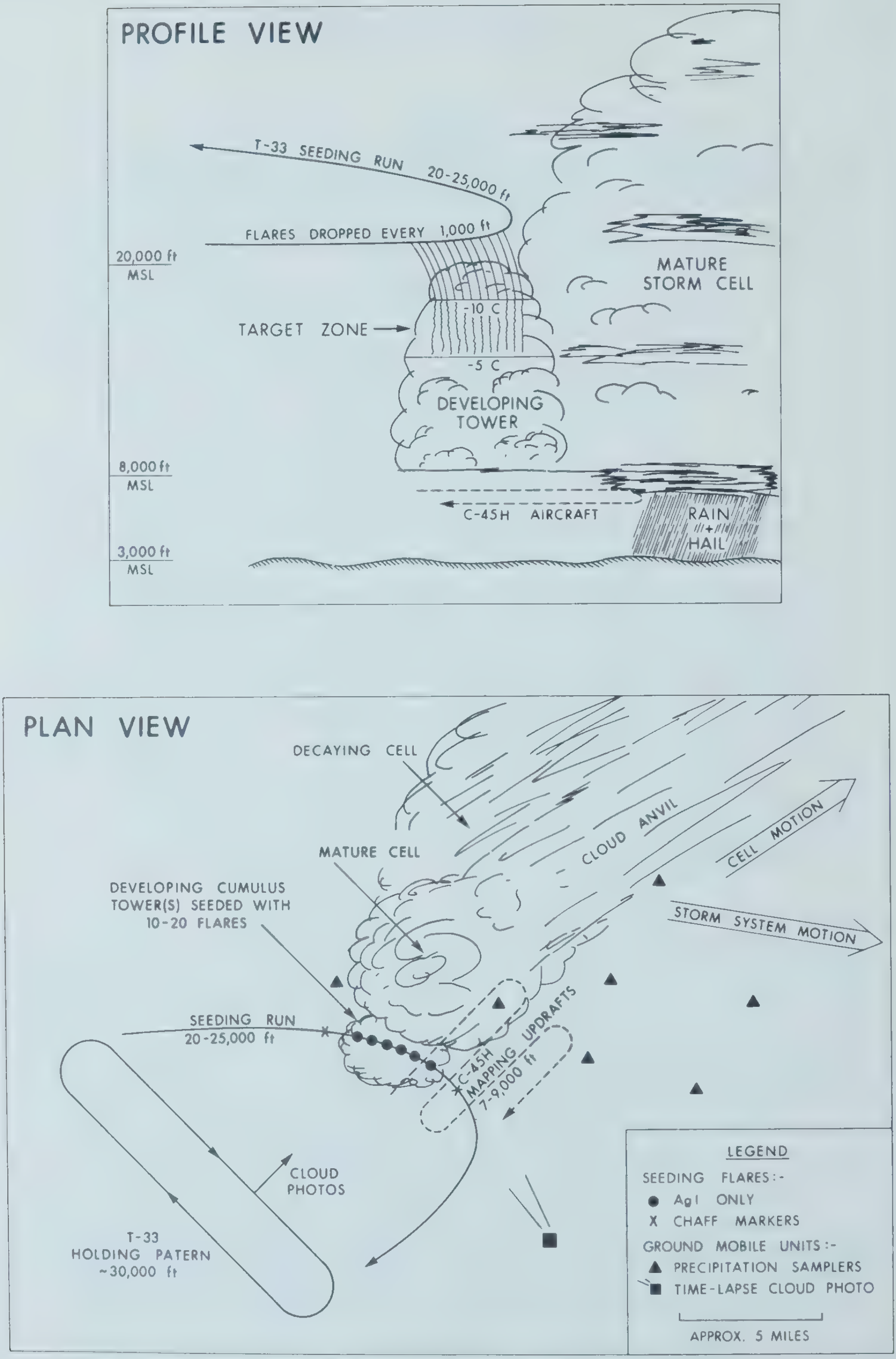

Fig. 8. Schematic illustration of the operational logistics for the seeding experiments.

given by the crew of the C-45H aircraft as they visually observed the advance of the precipitation curtain and hail shafts.

A mobile photography unit was deployed to the southeast of the target storm at a distance of 15 to 30 mi to record its visual appearance on 16-mm movie film with a 3 sec time lapse (Renick & Douglas 1970). After each experiment, telephone surveys were conducted to solicit precipitation reports from the farmers in the area traversed by the seeded and other storms. A full description of the Alberta Hail Studies field program and the observing systems is given by Renick (1970).

The five experiments conducted during July 1970 and the data obtained for evaluation of seeding effects are summarized in Table 8. The best documented experiment was conducted on 11 July and a detailed case study of this storm is now underway.

TURBULENCE MEASUREMENTS IN CUMULUS TOWERS

Turbulence levels and dissipation rates were measured in cumulus type clouds by a second T-33 aircraft from the National Aeronautical Establishment equipped with an analog tape recorder capable of measuring 25 different parameters (see Fig. 9). This aircraft was in Alberta for one week and accompanied the seeding aircraft on two days. The two aircraft flew in formation until the decision to seed was made. The second T-33 then made an initial penetration of the target cloud, leading the seeding aircraft by approximately one mile. After the seeding was accomplished, further penetrations were made.

Records of longitudinal gúst velocity obtained from the second T-33 were used to calculate dissipation rates within the clouds. Using the assumption of "local isotropy" due to Kolmogoroff the dissipation rate is related to the spectrum of longitudinal gusts by the relation,

$$S(1/\lambda) = \alpha\epsilon^{2/3}\lambda^{5/3} \qquad (1)$$

where S is the power spectral density $\left(\frac{(\mathrm{cm/sec})^2}{\mathrm{cycle/cm}}\right)$

ϵ is dissipation rate ($\mathrm{cm}^2\,\mathrm{sec}^{-3}$), λ is the wavelength (cm) and α is a universal constant ($\sim$0.147). To calculate ϵ, it is first necessary to compute the power spectral density at some particular wavelength. This was accomplished by means of a band pass filter and an averaging network with a time constant of 10 seconds. Depending on its length, each run was split into two or three segments, and dissipation rates were calculated using values of S averaged over each segment.

Table 8. Summary of cloud seeding experiments

Expt No	Date	Type of storm seeded	No. of flares		Data obtained for evaluation								
					Ground based				Airborne by C-45H aircraft			Airborne by T-33 aircraft	
			AgI only	AgI+ chaff	Radar	Time-lapse photo	Hail survey	Precip samples	Cloud-base fluxes	Precip samples	In-cloud data	Cloud photos	turbulence* measurements
1	July 9	Multi-cellular hailstorm	7	6	X		X	X	X	X		X	
2	11	Steady-state hailstorm	32		X	X	X	X	X			X	
3	17	Small Cu		4	X							X	X
		Cu congestus		4	X							X	X
4	20	Decaying hailstorm	15	2	X		X			X			X
5	30	Small Cu congestus	6	2	X	X	(no precipitation)		X	X	X	X	

*Measurements obtained by a second T-33 aircraft.

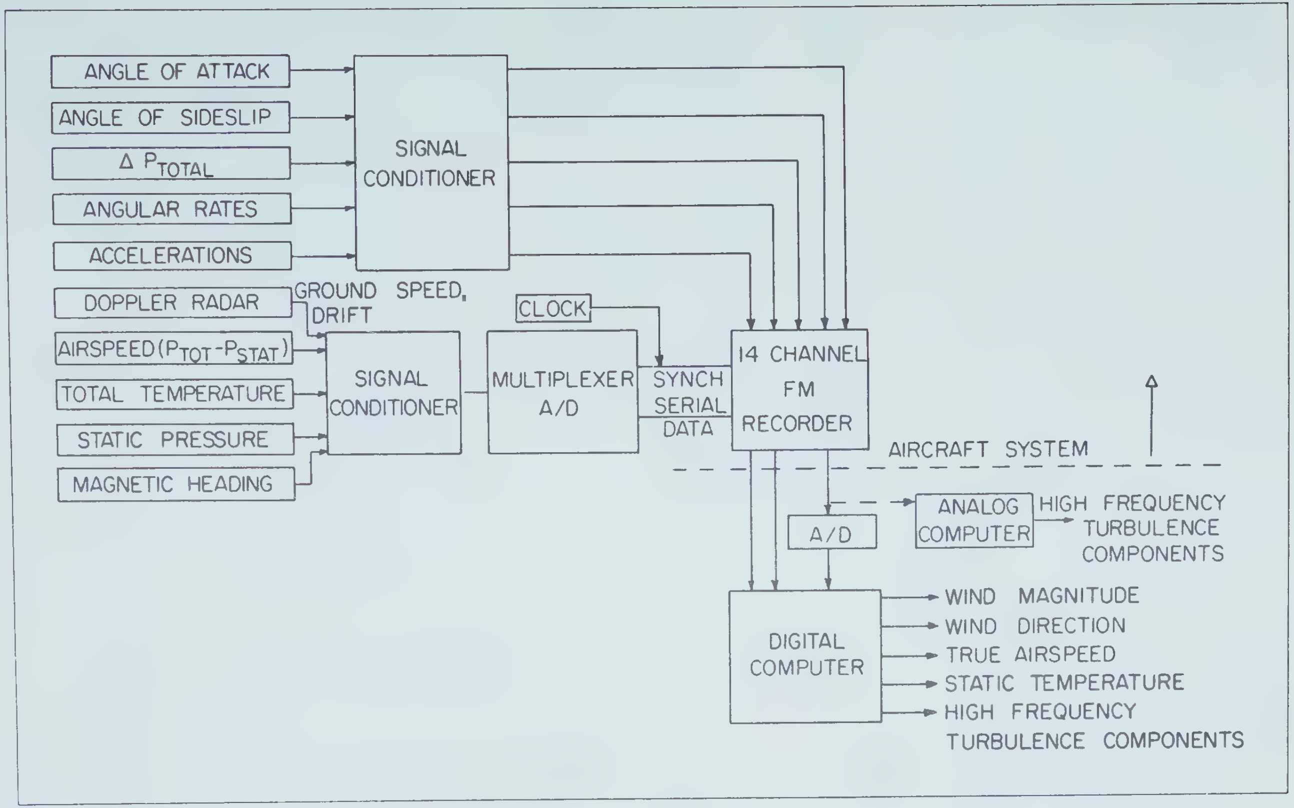

Fig. 9. Functional block diagram of the T-33 turbulence instrumentation system.

The vertical gust velocities were measured over a bandwidth of 0.05 to 10 cps. These were then averaged with an RC filter with a 10 sec time constant. The average updraft over each segment of the aircraft pass through the cloud was then found.

Table 9 summarizes the results obtained from penetrations of a cumulus, cumulus congestus and a decaying hailstorm. Figure 10 shows traces of the longitudinal gust component and the calculated power spectral density for three successive passes through the heavy cumulus. The first pass was made before the seeding run, the second immediately after seeding, and the third approximately 10 minutes after seeding. Results from the three passes suggest that shortly after seeding the turbulence intensity and dissipation rates and also the updraft increased noticeably and then decreased substantially after another 10 min. Average values of the dissipation rate found in the large cumulus towers are of the order of 1000 $cm^2 sec^{-3}$.

Table 9. Summary of turbulence dissipation rates and updrafts measured in cumulus clouds

Date	Altitude (ft)	Cloud type	Dissipation rate ($cm^2 sec^{-3}$) Segment of traverse 1st	2nd	3rd	Avg updraft ($m\ sec^{-1}$) Segment of traverse 1st	2nd	3rd
17 July 70	18,000	Small Cu	49	69		1	2	
17 July 70	18,000	Small Cu		73	25	0	-2	-3
17 July 70	18,000	Small Cu	136	95		2	1	
17 July 70	18,000	Cumulus congestus	269	1148	1314	0	-1	2
17 July 70	18,000	Cumulus congestus	465	1597	1731	-1	0	1
17 July 70	18,000	Cumulus congestus	102	669	584	0	0	1
20 July 70	18,000	Decaying storm	691	269	81	1	-2	0
20 July 70	18,000	Decaying storm	33	495	125	2	4	-2

ESTIMATES OF SEEDED VOLUMES AND NUCLEI CONCENTRATIONS

Using the seeding flare output and the turbulence measurements in the previous section, it is possible to obtain an order of magnitude estimate of the volume of cloud seeded and the concentration of freezing nuclei produced. For the purpose of these calculations the initial seeded path

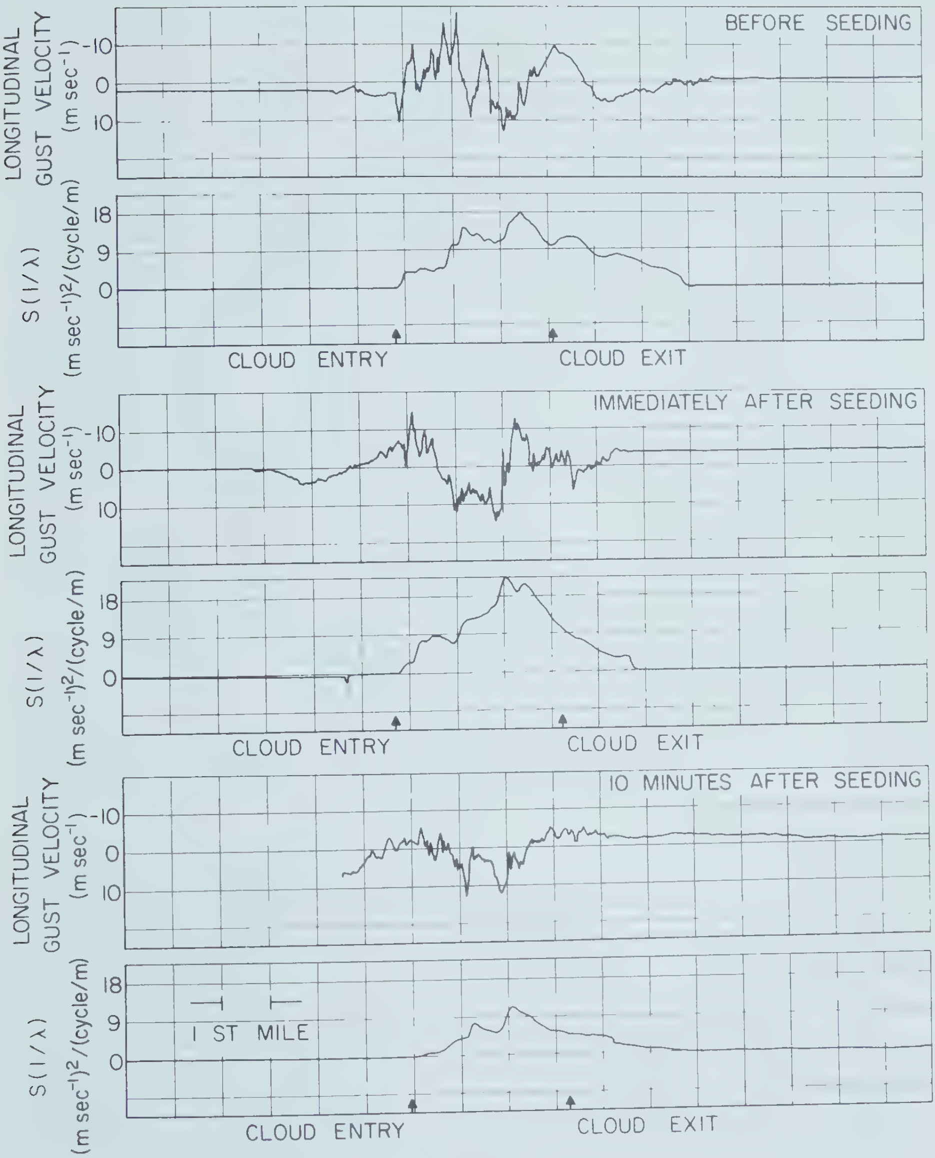

Fig. 10. Longitudinal gust component and power spectral density at 100 ft wavelength (5 Hz) for three successive penetrations of a cumulus congestus at 18,000 ft MSL on 17 July 1970.

length is assumed to be approximately 900 m (see Tables 2 and 3). Initially the falling flares produce a silver iodide line source of 0.028 gm m^{-1} which expands with time due to turbulence in the cloud to produce a seeded cylindrical volume. Following the simplified approach of MacCready and Vickers (1966), then the seeded plume diameter d (cm) after a time t (sec) is given by

$$d^2 = C \epsilon t^3 \qquad \text{for } t > 1000 \text{ sec} \tag{2}$$

where ϵ is the turbulent dissipation rate and C is a constant of the order of unity. From Table 9 the expected range of values for ϵ in the seeded zone of the developing cumulus towers is between 500 and 1500 $cm^2 sec^{-3}$. Using these figures and the fact that the initial seeded path length is 900 m and will be expanding in the vertical at a rate given approximately by Eq. (2), then the seeded volume is estimated for various times after seeding. The results for 2 min and 5 min after seeding are shown in Table 10. Initially the seeding material was put into the cloud between the -5C and -12C levels. After 2 min the nuclei concentration active at -10C is calculated. After 5 min, most of the seeding material will have risen in the cloud and so the nuclei concentration active at -15C is given in Table 10.

During the 1970 seeding experiments the flares were dropped every 2 sec, or approximately every 300 m, along the flight path. Table 10 shows that under the turbulence conditions likely in the target zone, the plumes from successive flares will be overlapping within 2 min of burn-out.

Table 10. Estimates of the seeded volume and ice nuclei concentration produced by each flare

ϵ ($cm^2 sec^{-3}$)	2 min after seeding				5 min after seeding			
	Plume dimensions			nuclei conc at -10C (l^{-1})	Plume dimensions			nuclei conc at -15C (l^{-1})
	diam (m)	length (m)	vol (Km^3)		diam (m)	length (m)	vol (Km^3)	
500	290	1190	0.1	2×10^3	1160	2060	2.9	6×10^3
1500	510	1410	0.4	6×10^2	2010	2910	12.3	1×10^3

After 5 min the seeding material will have diffused through a substantial volume and the resulting ice nuclei concentrations will be at least three orders of magnitude above natural background.

USE OF CHAFF IN THE FLARES

Radar chaff was incorporated in some of the flares for use as a means of checking on the targetting accuracy of the seeding system. The flares containing the chaff were otherwise identical to the no-chaff flares so that the same delay and burn times would apply. As seen from Table 4, the chaff flares tended to fall slightly further, particularly when dropped from higher altitudes, however the height difference represents a temperature difference of $< 1C$ and is therefore insignificant. If accurate height finding radar were used, then the difference between chaff and no-chaff flares could be corrected for if desired.

The chaff flares may be used in two ways. As a height marker, they are useful in confirming the fall distance of the flares when dropped into cumulus towers. Since the flares are falling for approximately 90 sec an error of 5 m sec^{-1} in the average updraft estimated from the tephigram would produce an error of 1500 ft in the burn-out altitude of the flare. This is equivalent to a target temperature error of approximately 3C. Since the cumulus towers are not normally producing a radar echo at the time of seeding, one or two chaff marker flares dropped on the seeding run may be used to confirm the targetting height accuracy.

Radar reflectivity and polarization measurements are being used as a primary tool for evaluation of the seeding experiments. It is therefore undesirable to put too much chaff into the seeded cloud volume. Even a small amount can have a marked effect on the polarization measurements because of the large axial ratio of the chaff. Experiments were performed on two small cumulus congestus clouds, on a day when few were producing echoes naturally,to assess the magnitude of these effects. Eight chaff flares were dropped into the clouds and polarization measurements were made with the radar. Turbulence measurements were also made within the cloud by the second T-33 aircraft to assess the rate at which the chaff diffused through the cloud.

The chaff flares can also be used as plan position markers. In this case the flares are dropped outside the target cloud at each end of the seeding run. The markers then positively identify the position of the seeded cloud before it produces a radar echo.

The size of the chaff bundle in the flares was sufficient for detection at a range of up to 35 or 40 mi with the Alberta Hail Studies radar.

CONCLUSIONS

The droppable pyrotechnic flare system was successfully adapted for use on a T-33 jet aircraft for seeding Alberta hailstorms. Recognition from the T-33 of new development on the southern flank of mature storms and subsequent seeding proved easier than anticipated. The one surprise was the quick reaction time required (~1 min) between recognition of developing cumulus towers and the initiation of the seeding pass. Good aircraft speed capability (~300 kt) is therefore considered essential to meet the requirements for this type of cloud seeding and hail suppression experiment.

In all cases, by means of radio communication between the T-33 aircraft and project ground control, it was possible to unambiguously identify and seed the target storm or cloud. The system is very flexible. Seeding rates can be varied by changing the spacing of flares dropped on a seeding pass. The height of the target zone can be varied by changing the delay burn of the flares or the drop altitude of the aircraft, or both.

Calculation of dissipation rates indicates that sufficient diffusion of the silver iodide will occur to produce freezing nuclei concentrations in excess of 100 per liter through large volumes of the cumulus towers within a few minutes of seeding.

Radar chaff released at the end of the flare burn is useful as a marker to check targetting accuracy. However its use is limited in range by the power and sensitivity of the radar system. The use of chaff in cloud is also limited because of its confounding effect on quantitative radar reflectivity and polarization measurements.

The seeding system now requires a full trial to ascertain whether the seeding concept is valid and whether this type of seeding can suppress hail damage caused by the persistent type of hailstorms. An expanded series of experiments is planned for the summer of 1971 in Alberta.

ACKNOWLEDGEMENTS

The authors wish to thank all the participants in the summer field program who contributed to the successful operation of the experiments, especially the Natural Resources Research Institute, University of Wyoming. Mr. J.H. Renick of the Research Council of Alberta supervised the photo-

grammetry of the night flare tests and their subsequent evaluation. These results are published with the permission of the Director of the National Aeronautical Establishment.

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